A Proposed Laser Safety Evaluation Plan for the Microvision, Inc., Scanning Laser Helmet-Mounted Display System

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Program Manager, Aircrew Integrated Systems (PM-ACIS) is developing a scanning laser helmet-mounted display (HMD) that can be fitted to the U.S. Army Helmet Gear Unit 56P (HGU-56P) aviation helmet. This HMD is manufactured by Microvision Inc., Bothell, Washington. This HMD system represents the first scenario in which aviators will be directly and purposely viewing laser energy. For this reason, in addition to standard required laser safety measures, an expanded effort is required to overcome ingrained aviator training to avoid exposure to laser energy.

This report presents a proposed laser safety evaluation plan, which is intended to both document laser energy exposure levels during normal and system failure conditions, as well as provide enhanced safety information considered instrumental in achieving aviation community acceptance of this new HMD technology.

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Introduction

Laser safety has been an important issue for the U.S. Army, as well as for the tri-service military community, for decades. The U.S. Army Medical Research Detachment of the Walter Reed Army Institute of Research at Brooks Air Force Base, San Antonio, Texas (formerly with the Letterman Army Institute of Research, Presidio of San Francisco, California) recognized laser technology and the issue of laser safety early on and since 1979 has hosted an annual Lasers on the Modern Battlefield (LMB) conference. This series of conferences has served as a platform for reviewing military laser-related vision, bioeffects, and safety research.

Systems and devices based on laser technology primarily have been developed and fielded for range finding and target designation applications. All three military services field systems for these applications. In addition, while there are no fielded systems to date, numerous programs have investigated laser-based weapons. The Army has looked at tactical uses of ground-based lasers, to include the feasibility of placing moderate to high-powered lasers on tanks or other heavily armored vehicles; the Navy has investigated the use of lasers as an anti-missile defense; and, the Air Force has studied the feasibility of using lasers in air-to-air combat (Mirra, 1989). At the individual level, evaluations of several commercially developed anti-personnel laser illuminators have been conducted by the Air Force (Apsey and Dennis, 2000).

The major focal point of laser safety is protection, for both personnel and systems. First in priority is protection against hostile lasers. This is followed by an emphasis on protection against exposures during force-on-force training exercises. Lastly, effort is being directed to protection against accidental self-exposure. Fortunately, whether due to these efforts or due to luck, there has been a low frequency of occurrence of severe laser injuries. However, evidence that work in all of these areas still is warranted can be found in recently reported incidents of exposure during the Gulf war conflict, in Bosnia, and in the training environment (Brown, 2000; Gorsuch, 2000). The U.S. Army Medical Research Detachment maintains a database of reported exposures in its Laser Accident and Incident Registry (LAIR).

The major focus of all previous efforts on laser protection has been to avoid exposing the skin and eyes to laser energy. Soldiers and aviators have been trained not to look into the laser beam. Now, for the first time, the Army is developing a system that by design directs laser energy directly into the eyes as a part of its normal operation. This system is the Microvision, Inc., Bothell, Washington, scanning laser helmet-mounted display (HMD), which uses two diode-pumped solid-state lasers emitting energy at 532 nanometers (nm) to present pilotage and targeting imagery. This novel, laser-based system originally was developed under a program initiated to explore potential alternate image technologies for use with the Aircrew Integrated Helmet System Program (AIHS, also known as the Helmet Gear Unit 56/P (HGU -56/P)). These programs have been directed by the Program Manager, Aviation Electronics Systems (PM-AES), Huntsville, Alabama.

As with any new system, a hazard analysis will be required to identify and mitigate safety concerns associated with the use and maintenance of this system. Inherent in this analysis will be the identification of laser energy levels that would be present during both normal and non-normal (i.e., failure) operation. Due to the system's novel image source, the safety issues

associated with this system have been a frequent topic of discussions during program reviews. To help address these concerns, Microvision has developed and implemented an in-house laser safety program. However, this system requires a more rigorous and independent safety analysis. This argument is based on two tenets. First, there is the innovation of using laser diodes as the image source. The introduction of any new image source could be accompanied by new and previously unidentified safety issues, and it is obvious that such is the case when laser diodes are involved. Second, the use of this laser-based system in the cockpit and its integration into a head-mounted system that will be worn by pilots during the entire flight period represent a paradigm shift in the role of lasers in military aviation. Pilots, long advised always to look away from lasers, now will be asked to fly wearing an HMD that continuously directs laser energy into their eyes. Such a shift in thinking necessitates a safety analysis that "goes the extra mile."

After providing a more detailed description of the operation of the Microvision HMD system and presenting a review of the safety data available on scanning laser technology in general, this paper outlines a proposed plan for conducting an expanded and rigorous laser safety evaluation of the Microvision scanning laser HMD.

Background

For more than 30 years, the Army has been developing and fielding HMDs in order to provide aviators with mission-essential flight information in a "heads-out" mode at night. In this period, the Army has fielded two primary HMD systems, the Aviator's Night Vision Imaging System (ANVIS) and the Integrated Helmet and Display Sighting System (IHADSS). ANVIS are flown in virtually all Army rotary-wing aircraft; the IHADSS is flown exclusively in the AH-64 Apache helicopter. ANVIS combine image intensification (I^2) sensors with a phosphor-based display, integrated into a single package. The IHADSS presents forward-looking infrared (FLIR) imagery from a nose-mounted thermal sensor on a miniature cathode-ray-tube (CRT) display. ANVIS are usable only during periods of low ambient light (i.e., night). IHADSS, while primarily a night system, can be operated, in a very limited sense, around the clock. See Verona and Rash (1989) and Rash et al. (1990) for expanded descriptions of these systems, respectively.

Day use of ANVIS is prohibited due to the limitation of input energy that the I^2 tubes can accept without damage. The ability to use the IHADSS during daytime flight is limited by the luminance output performance of the CRT. In fact, this inability of current HMD image sources (e.g., miniature CRTs, liquid crystal displays (LCDs), and electroluminescent displays) to provide sufficient luminance for acceptable usability against ambient backgrounds of up to 5,000 footlamberts is the major driver behind the development of the scanning laser HMD. Lasers as image sources offer distinct advantages over previous display technologies (Lippert et al., 2000a,b). For one, luminance with lasers is limited only by eye-safety and power considerations. The light-concentrating aspect of the diffraction-limited laser beam can routinely produce source luminances that exceed that of the solar disc.

The Microvision scanning laser HMD

Microvision is developing multiple HMD designs based on the technique of scanning lasers. The AIHS configuration, which is the system of concern herein, is a monochromatic design based on "green" lasers emitting at 532 nm. However, other ongoing designs incorporate red, green and blue lasers for full color applications, and appropriate laser hazard evaluations for these alternate configurations also will be addressed at future dates. An artist's depiction of the schematic diagram illustrating the functional components of a proposed tri-color (three laser) system is presented in Figure 1. Figure 2 extends the artist's conception to depict the ability of scanning laser HMDs to present symbology of sufficient luminance to be seen against daytime backgrounds.
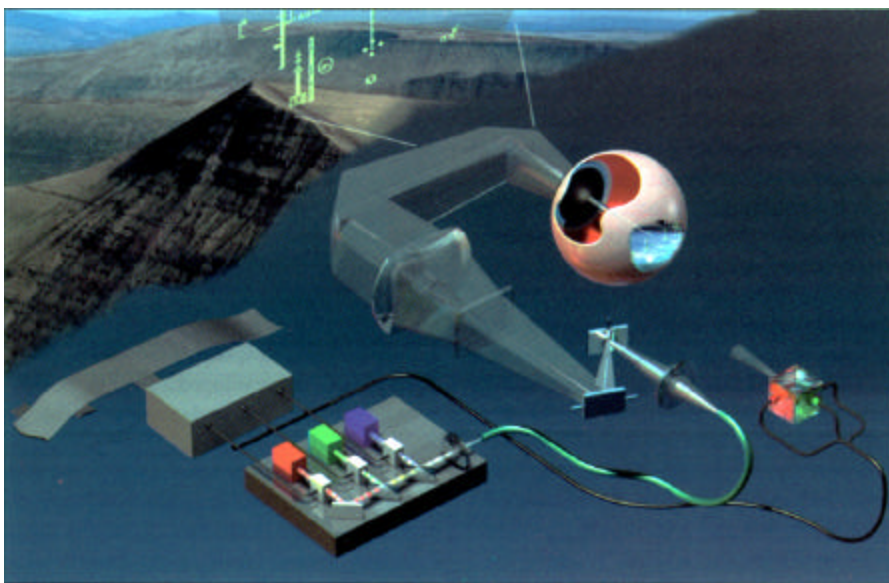
Figure 1. An artist's depiction of the schematic diagram illustrating the functional components of a tri-color (three laser) system (Lippert et al., 2000a).

The AIHS scanning laser HMD design is intended for use in the Army rotary-wing environment. It is a monochromatic, binocular system that is required to provide a 52° horizontal by 30° vertical field-of-view (FOV) with a 30° overlap, a 15-millimeter (mm) exit pupil, and 25 mm of physical eye relief. It incorporates two 532 nm lasers, one per eye, operating in a bi-directional scanning mode. It has a requirement to provide luminance values in excess of 1200 footlamberts (fL). A summary of system requirements is provided in Table 1.

The current HMD system prototype consists of several primary components: an HMD comprised of a Pilot Retained Unit (PRU) (helmet) and an Aircraft Retained Unit (ARU) (Figure 3); an electronic and control module; interconnect cables and three lap top computers, two of which control imagery to the two HMD channels and a third which provides control of the electronic components; and, a power supply that provides an external voltage source for

controlling the HMD imagery luminance. Size and number of components continue to decrease as development continues.

Figure 2. An artist's conception depicting the ability of scanning laser HMDs to present symbology of sufficient luminance to be seen against daytime backgrounds.
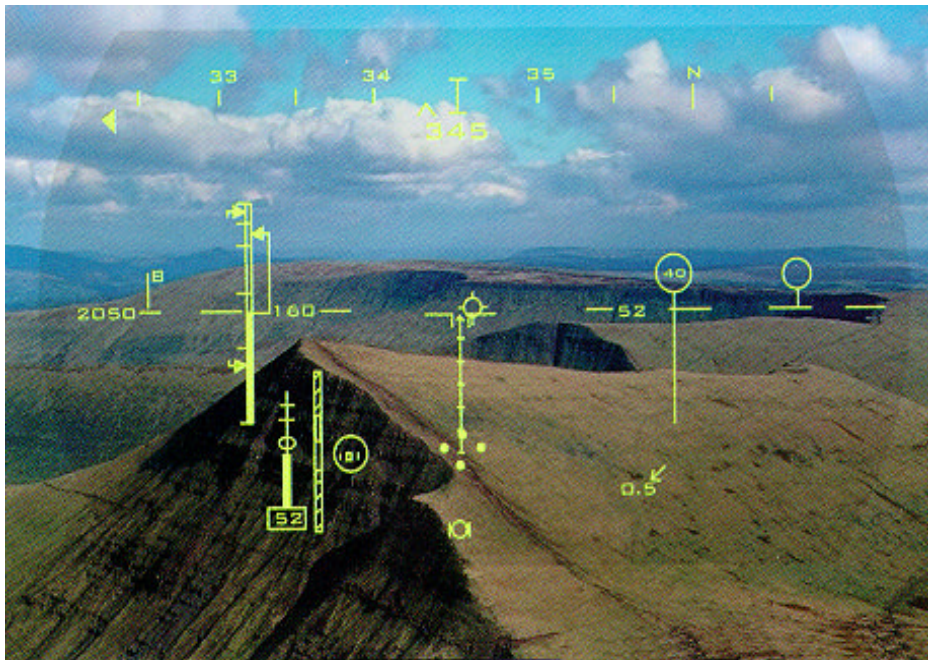

Figure 3. Microvision prototype scanning laser HMD.

Table 1.

Summary of requirements for AIHS scanning laser HMD.

Parameter	Requirement
HMD Type	See-through
Color	Monochrome – Green
Configuration	Binocular
Field of view	52° x 30° (H x V)
Overlap	30° minimum
Resolution	1280 x 960
Luminance @ the eye	1200 fL
Exit pupil (On axis)	15 mm
Eye relief distance	25 mm
Helmet	HGU-56/P

Functional operation

   As described previously, the AIHS system consists of two channels, one per eye. A functional block diagram of the system is provided in Figure 4. The diagram includes the power supply/management and drive (video processing) electronics subsystems, which are shared by the two channels, and those subsystems that are found in each channel: light source (photonics) module, fiber-optic cable, scanner assembly, exit pupil expander (EPE), and relay/viewing optics. A brief description of each subsystem follows:

1. Power supply/management. Supplies required analog (+12V, +/-5V), digital (+5V, +3.3V), and driver (+24V, +12V) voltages to all other subsystems.

2. Drive (video processing) electronics. Receives and processes signals from an image source. The processed signals contain information that controls the intensity and coordinates to position the individual picture elements (pixels) that comprise the image, i.e., provides signals that encode the image information onto the laser beams and control the timing synchronization of the horizontal and vertical scanners in the scanner assembly.

3. Light source (photonics) module. For each channel (eye), this subsystem consists of one diode-pumped solid-state laser [currently a Coherent model 315M-100, 100 milliwatt (mW) continuous wave laser] (Figure 5), a slow acoustic-optic modulator (AOM), a holographic beam splitter, a dual AOM, and associated folding and focusing optics. Table 2 provides a summary of laser specifications. The slow AOM serves to attenuate the intensity (brightness) of the initial laser beam. The beam splitter divides the initial laser beam into two beams. The two beams are directed to the dual AOM which when coupled with the signals from the drive electronics produce the image data pulse stream.

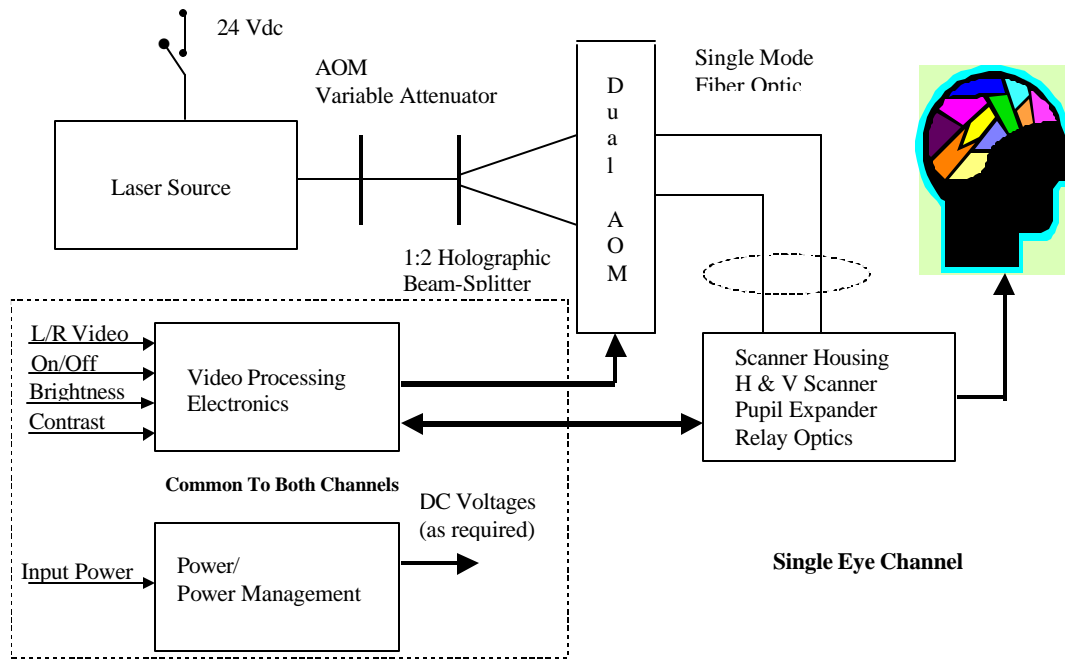Figure 4. Functional block diagram of scanning laser HMD system.

Figure 5. Representative diode-pumped solid-state laser.

Table 2.

Laser specifications.

Parameter	Specification
Wavelength	532 nm Green
Output power	100 mWatts
Spatial mode	TEM_{00}
Roundness of beam	>95%, <1.1:1.0
Beam diameter ($1/e^2$)	0.32 ± 0.02 mm
Beam divergence	< 2.2 mrad

4. Fiber-optic cable. Consists of two single-mode fibers, one per beam. This cable brings the laser beams from the aircraft-mounted enclosures that house the lasers, drive electronics, power supply, etc., up to the scanner assembly and relay/viewing optics located on the head.

5. Scanner assembly. Consists of the horizontal and vertical scanners that "paint" the image by rapidly moving the light source across and down, in a non-interlaced raster pattern. The horizontal scanner is a bi-directional mechanical resonating scanner (MRS) operating typically at 15.75 kilohertz (kHz). The vertical scanner is a linear galvo-mechanism operating at 60 Hz. [Note: Microvision is working on the development of a Micro-Electro-Mechanical Systems (MEMS) technology scanner that will perform the functions of both the horizontal and vertical scanners within a single element. MEMS technology is the integration of mechanical elements, sensors, actuators, and electronics on a common silicon substrate through the utilization of microfabrication technology.]

6. Exit pupil expander (EPE). Currently a diffractive optical element (may be holographic in final design) that increases the size of the effective exit pupil. Nominally, the image would be contained in an area of 1 mm^2. The EPE increases the natural output angle of the image and enlarges it up to approximately 15 mm in diameter (~177 mm^2) for ease of viewing. The raster image created by the horizontal and vertical scanners passes through the pupil expander and on to the viewer optics. Note: When the exit pupil is observed, as in the photographic setup in Figure 6 (left), the exit pupil appears as a set of beamletts [Figure 6 (right)]. Each beamlett contains the entire image.
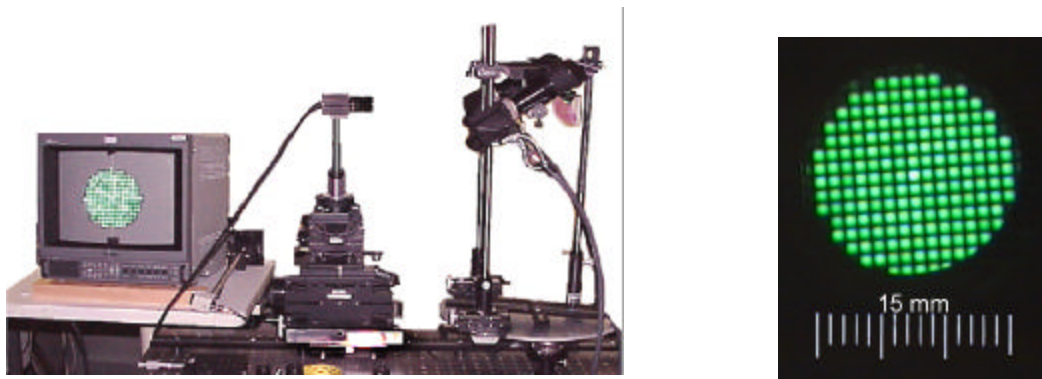
Figure 6. When the exit pupil is observed, as in the photographic setup (left), the exit pupil appears as a set of beamletts (right).

7. Relay/viewing optics. Consists of multiple refractive and reflective optical elements that relay the final image to the eye. The current optical design is that of a folded catadioptric optical train. The present ocular implementation is shown in Figure 3. While the exact design is proprietary in nature, a generic representation of the folded catadioptric design is shown in Figure 7.
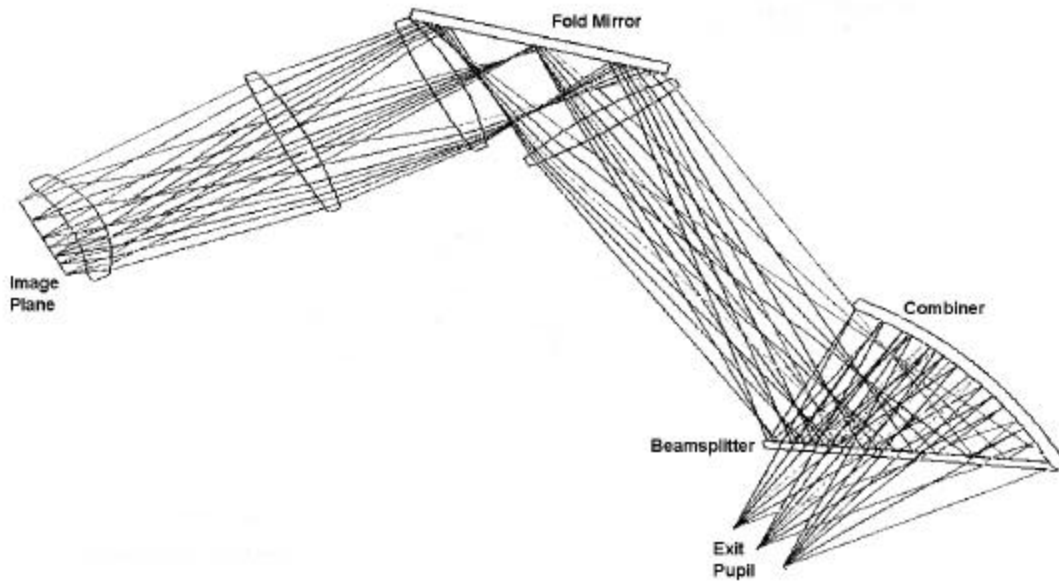
Figure 7. Generic representation of the folded catadioptric design.

Optical-path description

The functional block diagram in Figure 4 is useful for the understanding of the operation of the Microvision AIHS scanning laser HMD. For the purpose of this paper, to propose an approach and methodology to its laser safety evaluation, it may be more interesting and useful to look at the system from the perspective of how the laser light (energy) traverses the optical path from laser source to the eye. A flow diagram of this path is presented in Figure 8. This diagram is applicable to both channels.

Step 1. Light beam leaves laser as single beam. Laser is 100 mW at 532 nm.

Step 2. Beam is fiber-optically coupled to slow AOM. Efficiency of coupling is approximately 100% resulting in approximately 100% of the energy initially delivered by the laser.

Step 3. Single beam enters slow AOM, which acts as an intensity modulator (45 dB dynamic range). Insertion efficiency is approximately 96%; diffraction efficiency is approximately 90%. Therefore, approximately 86.4% of the energy delivered by the laser leaves the slow AOM.

Step 4. Beam enters holographic beam splitter that produces two primary beams and several extraneous low energy beams. These extraneous beams are absorbed within the AOM. Beam splitter has efficiency of approximately 65%. Therefore, approximately 56% of the energy initially delivered by the laser leaves the beam splitter. However, since this energy is now divided between two beams, each beam exits with only 23% of the initial laser energy.
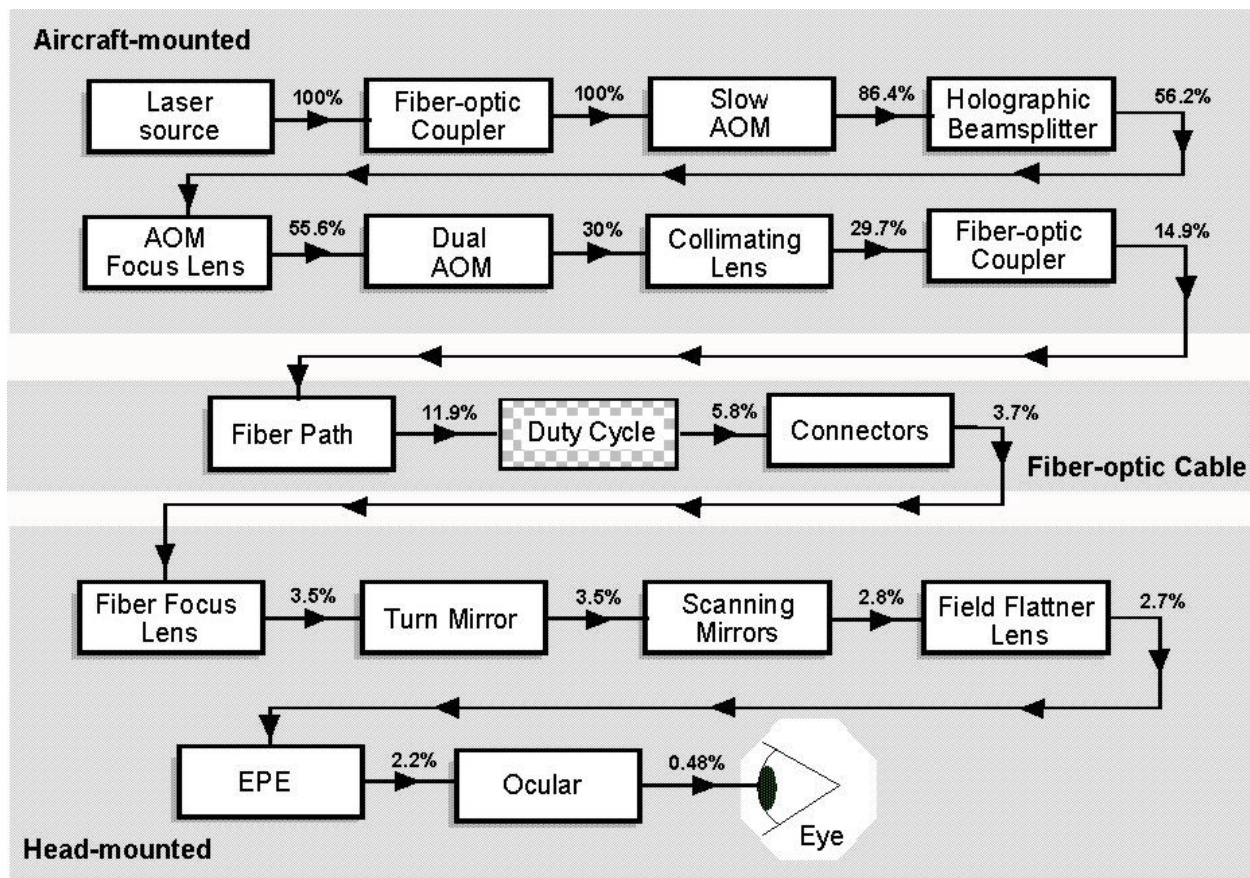
Figure 8. Flow diagram for optical path of laser energy.

The path of the laser energy consists of the following steps:

Step 5. Both beams enter into a single AOM focus lens that results in two spots of 30-35 micron diameter ($1/e^2$). This lens has efficiency of approximately 99%, resulting in approximately 55.6% (27.8% per beam) of the initial laser energy exiting the lens.

Step 6. Each beam then enters a dual AOM where each is modulated by drive signals provided by the video processing electronics. With an insertion and diffraction efficiencies of 90% and 60%, respectively, the dual AOM has a total efficiency of approximately 54%, resulting in 30% (15% per beam) of the initial laser energy exiting the dual AOM.

Step 7. Each of the two modulated beams exiting the dual AOM enters a collimating lens of 99% efficiency. Approximately 29.7% (14.85% per beam) of the initial laser energy exits this lens.

Step 8. Each focused beam enters a fiber-optic coupler that mates the beam to a single-mode optical fiber for transmission to the head-mounted components. With an efficiency of 50%, approximately 14.9% (7.45% per beam) of the initial laser energy is delivered through the coupler.

Step 9-11. Each beam traverses its respective fiber up to the HMD. Combined fiber transmission, duty cycle and connector efficiency is 25.1% resulting in 3.7% (1.85% per beam) of the initial laser energy.

Step 12. Each beam exits the fiber through a fiber focus lens of 94% efficiency resulting in 3.5% (1.75% per beam) of the initial laser energy.

Step 13. Both beams are reflected off a turn mirror (or pinch mirror if pinch correction provided). With greater than 99% efficiency, the resulting energy is 3.5% (1.75% per beam) of the initial laser energy.

Step 14. Both beams are bi-directionally scanned by horizontal and vertical scanning mirrors. Efficiency of scan mirrors is approximately 81%. The resulting energy is 2.8% (1.4% per beam) of the initial laser energy.

Step 15. Both beams pass through a negative lens acting as field flattener lens. Efficiency is 98%. The resulting energy is 2.7% (1.35% per beam) of the initial laser energy.

Step 16. Both beams enter EPE where they are diffracted (or holographically) expanded into an array of beamletts. Each beamlett contains the entire scanned image. EPE efficiency is 80%. The resulting energy is 2.2% (~1% per beam) of the initial laser energy.

Step 17. Beamletts enter the ocular, pass through a series of optical elements, and reflect off the combiner elements.   Total ocular efficiency is approximately 22%. The resulting energy finally delivered to the eye is 0.48% (0.24% per beam) of the initial laser energy. A recent evaluation (Harding et al., 2001a) reported a luminance at the eye of 1485 fL. This implies that laser output luminance was of the range of 309,000 fL. By analogy, based on the 100 mW laser output, the system theoretically should deliver approximately 0.48 mW of power to the eye.

Step 18. Several of the beamletts enter the eye providing the viewed image. Since not <u>all</u> of the beamletts enter the eye, total energy delivered to the eye will be less than that predicted by this analysis. Since the higher luminance setting used in the daytime scenario would result in a light adapted pupil of approximately 4 mm diameter, the ratio of the pupil's area to the area of the exit pupil would be 16:225. Therefore, the eye would be receiving only about 7% of the total energy delivered by the system within its full exit pupil.

Note: The efficiencies presented here are representative of values obtained to date. These values may differ from those achieved in the final design.

   In early descriptions of this system, the terminology of "Virtual Retinal Display (VRD)" was used. This is a misnomer, and more recently an effort has been made to refer to this system as a retinal scanning display (RSD). By definition, a true VRD scans the modulated laser energy directly onto the retina of the viewer's eye(s). The image is formed directly on the retina; no intermediate image is formed. However, in the Microvision AIHS system, the scanning of the laser beams forms an intermediate "real" image, which then in turn is viewed by the eye.

Figure 9 is a pictorial representation of how the final image is formed for three viewing scenarios. In the top of Figure 9, a pixel-based display such as a cathode-ray-tube (CRT) is depicted. The object pixel on the display is imaged by the eye unto the retina. Since CRT pixels consist of small areas of a phosphor material that are excited by an electron beam, the energy output of the pixel, and hence the energy irradiation unto the imaged pixel on the retina, has a decay time distribution as shown in the small insert.

In the middle of Figure 9, image formation for a true VRD is shown. The laser scans the full image directly unto the retina. Each pixel related area of the image on the retina is exposed only for the brief time period that the laser is traversing that area. For the center of the image, that time is approximately 12.4 ns; for the edge of the image, pixel dwell time is approximately 30.0 ns. The energy exposure graph is represented as relatively narrow spikes.

Image formation for the Microvision scanning laser display is depicted at the bottom of Figure 9. The laser draws (scans) out the image at the EPE. The relay optics then magnifies the EPE output, which is viewed by the eye. The major difference between this configuration and the true VRD is that an intermediate image (at the EPE) is formed and then viewed by the eye.

History of scanning laser displays

The concept of scanning a laser beam into the eye is generally credited to Webb et al., (1980) and Webb (1982) in their development of a scanning laser ophthalmoscope (SLO). However, in their design, the scanning laser energy was not being directly used to create images. Instead, it was a method to receive reflected laser light back from the retina through the optics of the eye. This reflected energy was used to produce a video picture of the retina (Pryor et al., 1998).

In one of the first designs that used a scanned light source to produce a viewable image, Reiss (1990) demonstrated the Private Eye, a small, lightweight display that swept out a two-dimensional virtual image formed by a modulated one-dimensional light emitting diode (LED) array and a moving mirror. The idea of replacing the LEDs with a laser was investigated by Kollin (1993) and Holmgren and Robinett (1994), among others. From the mid 1990s to the present, researchers at the Human Interface Technology Laboratory (HITL), University of Washington, have been at the forefront of retinal scanning technology to include engineering development and applications (Kollin, 1993; Tidwell, M., 1995; Kollin and Tidwell, 1995; Viirre et al., 1998). Working initially with HITL (Johnston and Willey, 1995), Microvision Inc. has adapted the VRD design and has performed additional research in the areas of EPEs (Powell and Urey, 2002) and scanning technologies (Urey et al., 2002; DeWitt and Urey 2002) to develop the RSD system under discussion in this paper.
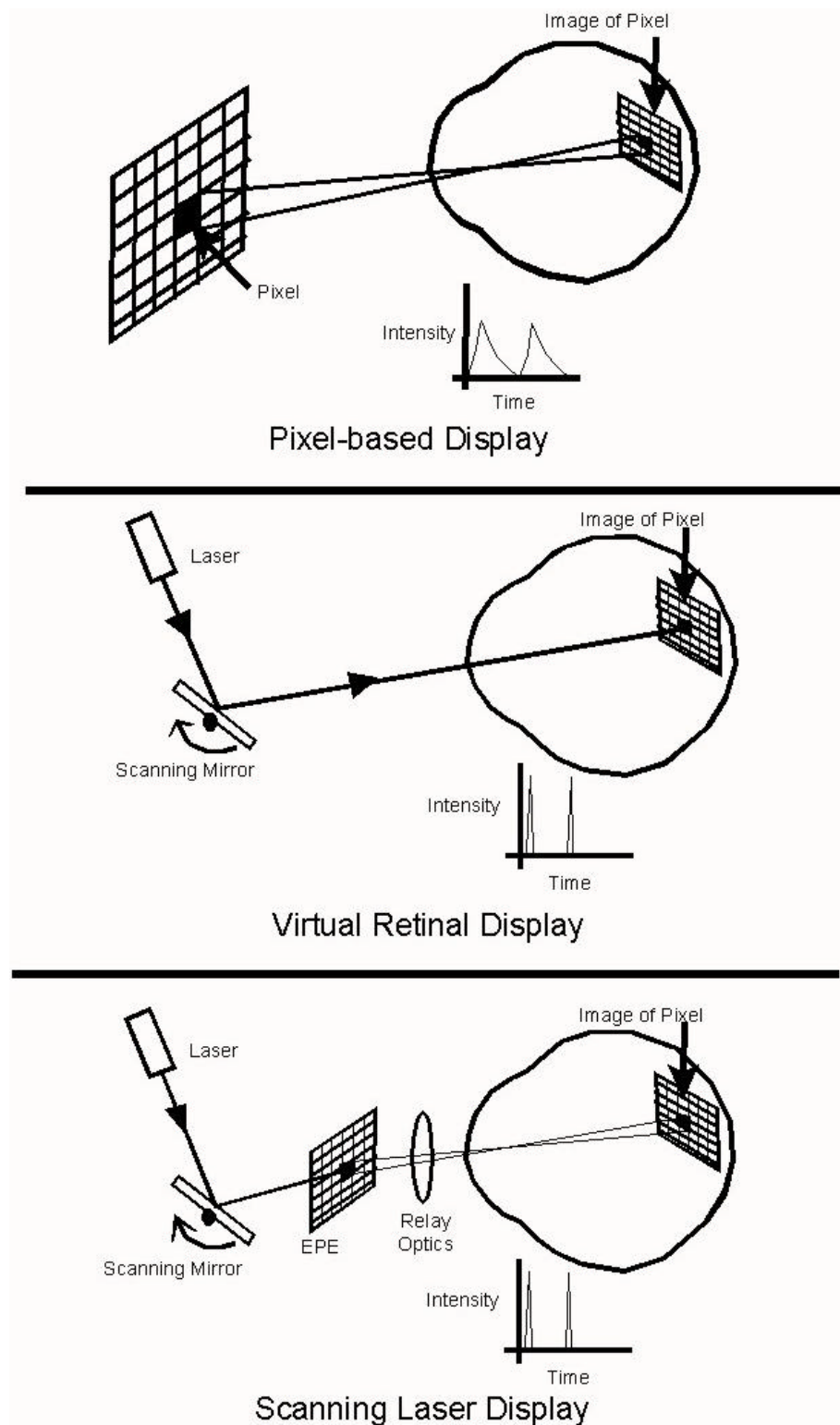
Figure 9. Pictorial representation of image formation for viewing a typical pixel-based display (top), a VRD (middle), and a scanning laser display such as the Microvision AIHS system (bottom) (Adapted from Viirre et al., 1990.)

Theoretical hazard analysis

The American National Standards Institute (ANSI) publishes a standard "For Safe Use of Lasers (Z136.1)." ANSI Z136.1 provides comprehensive information on laser classifications, hazard analysis and control measures needed for the development of a comprehensive laser program, and this standard provides maximum permissible exposure (MPE) values for various laser applications. The Army uses MIL-STD-1425A – 1991, Safety Design Requirements for Military Lasers and Associated Support Equipment. Purpose, for to provide uniform requirements for the safe design of military equipment that incorporates lasers. These requirements apply only to laser products designed expressly for combat or combat training operations or are classified in the interest of national security. This MIL-STD adopts the ANSI Z136.1 definitions as the best compromise and most current and comprehensive standard available when this MIL-STD was written. Additionally, this MIL-STD adopts the MPE exposure levels in ANSI Z136.1.

The MPEs presented in ANSI Z136.1 are categorized for extended and intra-beam sources by the characteristics of the source. Extended-source viewing occurs when the source consists of laser light reflected from a diffuse surface. ANSI Z136.1 defines an extended viewing source as one subtending an apparent visual angle at the pupil equal to or greater than 1.4º for exposure durations equal to or greater than 10 seconds. Intra-beam viewing occurs when the pupil of the eye intercepts a collimated (or nearly collimated) laser beam. However, the 2000 version of ANSI Z136.1 (currently the most widely distributed version) does not explicitly address the VRD/RSD situation of intrabeam viewing of a scanned source and led to uncertainty in the determination of appropriate MPEs for scanning laser systems (Li and Rosenshein, 1993; Viirre et al. 1990). Consequently, discussions of safety considerations for scanning laser ophthalmoscopes (Klingbeil, 1986; Li and Rosenshein, 1993) and VRDs (Viirre et al., 1990, 1997) have adopted very conservative approaches to the setting of MPEs for these systems. However, since the Microvision AIHS system under discussion herein has a scanned field of approximately 30º x 41º, it is generally agreed that the appropriate category for this system is that of an extended source. [Note: ANSI Z136.1-2002 has just been released and does address VRDs. It has yet to be widely disseminated and implemented by the laser industry. Its implications for the Microvision system will be addressed in a future analysis.]

The eye transmits and focuses energy over the wavelength range of 400 to 1400 nm, which therefore defines the retinal hazard range. For the visual/near-infrared wavelengths of 450-850 nm, the average transmission through the ocular media is approximately 80 percent (Boettner and Reimer Wolter, 1962). The AIHS system laser emits at 532 nm for which the ocular media transmission is approximately 93 percent.

For continuous wave (CW) lasers, the two most prevalent injury mechanisms for the retina are thermal damage and photochemical damage. Thermal damage is the primary mechanism for longer wavelengths ($\lambda > 550$ nm). Photochemical damage is more predominant for shorter wavelengths with exposure periods of greater than 10 seconds. Damage from pulsed lasers is caused mainly by a shock-wave mechanism. By definition a pulsed laser is one having a pulse width of less than 0.25 seconds. However, pulse widths must generally be in the range of tens of

nanoseconds or less in order to cause the mechanical or shock damage (Winburn, 1985). For normal operation, each corresponding pixel area on the retina is exposed to the scanning laser beam once every 16.67 ms (based on a frame rate of 60 Hz) and for a period of duration of approximately 12 ns at the center of the display and approximately 30 ns at the periphery. Therefore for normal operation, exposure is analogous to that of a pulse laser having a pulse width of 12 ns (30 ns at periphery) and a pulse repetition rate of 60 Hz.

Viirre et al. (1990) conducted a thorough laser safety analysis of a true VRD for both normal operation and several possible failure modes. Their analysis assumed extremely conservative parameters, such as 8 hours of continuous exposure. The calculated power levels indicated the VRD to be safe for both normal and failure modes. While the Microvision system is not a true VRD and the system parameters are different from those in the following analysis, the approach used by Viirre et al. (1990) has good applicability and is worth presenting here as a worst case analysis.

Calculations of MPE were first made by considering the scanned VRD as a pulse laser and then determining the MPE per pulse. Next, the VRD was considered as an extended source. An eye entrance pupil size of 7 mm, corresponding to an area of 0.385 cm^2, was assumed.

MPE for pulsed lasers – The MPEs for 12 ns and 30 ns pulses at 532 nm from ANSI Z136.1 Table 5 are both 0.5 x10 $^{-6}$ Joules (J)-cm^{-2}. For an 8-hour (3 x 10^4 seconds) exposure, the total number of pulses (n) at the 60 Hz frame rate is 1.8 x 10^6. To correct for repeated pulses, a correction factor of $n^{-1/4} = 0.0273$ is used in the following MPE calculation assuming the beam is dispersed over the entire entrance pupil of the eye:

$$\text{MPE}_{\text{pulse}} = (0.5 \text{ x}10^{-6} \text{ J-cm}^{-2}) (0.385 \text{ cm}^2) (0.0273) = 5.25 \text{ x } 10^{-9} \text{ J}$$

For the Microvision pixel dwell times of 12 ns and 30 ns, the $\text{MPE}_{\text{pulse}}$ is equivalent to 0.4375 and 0.175 Watts (W), respectively.

MPE for CW sources – As a second method, the exposure was calculated as a CW laser source dispersed over a given area. $\text{MPE}_{\text{pulse}}$ was calculated by dividing by the pulse rate. From ANSI Table 5, the MPE for a continuous source for wavelengths between 400 nm to 550 nm is 10^{-6} W cm^{-2}. By this method,

$$\text{MPE}_{\text{pulse}} = (10^{-6} \text{ W-cm}^{-2}) / (60 \text{ pulses per second}) = 16.67 \text{ x } 10^{-9} \text{ J cm}^{-2}$$

The overall MPE was the $\text{MPE}_{\text{pulse}}$ divided by the pulse durations (12 ns and 30 ns) and multiplied by the aperture is:

$$\text{MPE} = (16.67 \text{ x } 10^{-9} \text{ J cm}^{-2} / 12 \text{ x } 10^{-9} \text{ sec}) (0.385 \text{ cm}^2) = 0.5348 \text{ W}$$

and

$$\text{MPE} = (16.67 \text{ x } 10^{-9} \text{ J cm}^{-2} / 30 \text{ x } 10^{-9} \text{ sec}) (0.385 \text{ cm}^2) = 0.2139 \text{ W}$$

These values were essentially equivalent to those obtained in method one.

A second approach to the MPE calculations was to treat the system as an extended source. This was based on the fact the scanned image is swept out over an angular extent of approximately 41° x 30°. This has been the approach used in the analyses of scanning laser ophthalmoscopes (Li and Rosenshein, 1993).

MPE for extended sources for pulses - For the approximately 41°- x 30°-scan size for the Microvision RSD, the solid angle is approximately 0.36 steradiance (sr). For extended sources greater than 0.1 radians and less than 0.7 seconds in duration, ANSI Appendix B3.2 gives the MPE as (8.5×10^3) (MPE_{pulse}), which for the above factors of pulse width, pulse repetition, and aperture area, results in a pulse extended source MPE value of 4.46×10^{-5} J-sr^{-1}. For a frame period of 16.67 ms:

$$MPE_{pulsed \ extended \ source} = (4.46 \times 10^{-5} \ J \ sr^{-1}) / (16.67 \times 10^{-3} \ ms) = 0.0027 \ W\text{-}sr^{-1}$$

Thus, for a 0.36 sr display,

$$P_{max} = (0.0027 \ W\text{-}sr^{-1}) \ (0.36 \ sr) = 0.0010 \ W$$

Klingbeil (1986) suggested a correction factor of 0.8 be used to correct for the short-term temperature effects of scanning. Using this correction factor,

$$P_{max} = 0.0008 \ W$$

Extended source by video frame - In the last MPE calculation for normal operation, the source was considered as covering a whole video frame (operating at 60 Hz). This method required the use of an extended source correction factor (C_E), which is obtained from ANSI Table 6. For an extended source with a pulse duration of less than 0.7 seconds, and a source size of greater than 100 mrad, $C_E = 1.15 \times 10^3$. Therefore, for an extended source with an exposure greater than 10 seconds:

$$
\begin{aligned}
MPE_{extended \ source} &= (C_E) \ (MPE \ ANSI \ Table \ 5) \ W\text{-}cm^{-2}\text{-}sr^{-1} \\
&= (1.15 \times 10^3) \ (10^{-6}) \ W\text{-}cm^{-2}\text{-}sr^{-1} \\
&= 0.00115 \ W\text{-}cm^{-2}\text{-}sr^{-1} \\
&= 1.15 \times 10^{-3} \ W\text{-}cm^{-2}\text{-}sr^{-1}
\end{aligned}
$$

For the 0.385 cm^2 aperture area,

$$
\begin{aligned}
MPE_{extended \ source} &= (C_E) \ (MPE \ ANSI \ Table \ 5) \ W\text{-}cm^{-2}\text{-}sr^{-1} \\
&= (0.00115 \ W\text{-}cm^{-2}\text{-}sr^{-1}) \ (0.385 \ cm^2) \\
&= 4.43 \times 10^{-4} \ W\text{-}sr^{-1}
\end{aligned}
$$

Since each video frame lasts only 12.19 msec, the power per frame is

$$MPE_{Frame} = 6.05 \times 10^{-4} \ W/sr$$

For the 0.36 sr display area and the 0.8 Klingbeil correction factor:

$$MPE_{\text{video frame extended source}} = (4.43 \times 10^{-4} \text{ W-sr}^{-1}) (0.36 \text{ sr}) (0.8)$$
$$= 1.28 \times 10^{-4} \text{ W,}$$

So far the analysis addressed the calculation of MPEs only for normal operation. Of equal, if not greater concern, are scenarios where total scanning failure has occurred, the source is reduced to a single point, and the exposure becomes one of a CW laser.

When both horizontal and vertical beam scanners fail, a single spot of exposure on the retina would result. Assuming the worst case (that laser output is continuous rather than pulsed), a value of approximately 1 mW was obtained.

The above analysis provides conservative benchmarks for comparison of theoretical and measured power levels for the Microvision system under development.

The Microvision laser safety program

The importance of the laser safety issue in the development of the Microvision AIHS system was emphasized in the earliest phases of the program. In the first specification/statement-of-work (Aircrew Integrated Systems, 1997), an "Eye Safety" section (Section 3.2) was present. The section read:

> "The contractor shall document and provide data showing the eye safety of all critical VRD (virtual retinal display) components. A report of these findings shall be submitted in accordance with Contract Data Requirements List (CRDL) A003 and presented at the designated Review."

To address this requirement, Microvision has developed an ongoing in-house laser safety plan. The overall objective of this plan is to validate the claim of the inherent safety of the AIHS design and to address potential hazards associated with various failure modes. While hazard analysis is a standard course of action for all newly developed systems, Microvision has designated laser safety as an especially critical element of the hazard analysis for the AIHS system.

Under the in-house plan, Microvision has identified appropriate rules and regulations that deal with the safety of laser products and, specifically, has worked to achieve full compliance with the Food and Drug Administration (FDA) Center for Devices and Radiological Health (CDRH) and the International Electrotechnical Committee's (IEC) regulations. Microvision also has retained the consulting services of several internationally recognized experts on laser safety for the purpose of reviewing the details and progress of the in-house laser safety plan.

As an early step in addressing laser safety concerns, Microvision performed calculations to predict power density levels both at the cornea and retina of the eye during normal and scanning failure modes. Basic assumptions in this analysis were the 532 nm wavelength of the laser source, a 15-mm exit pupil, a measured 41° x 30° FOV per eye, and a luminance of 1470 fL (5042 Cd/m^2) at the eye.

Corneal power density at the eye can be calculated using the following expression:

$$P(8)/A = L(8)*\Sigma/K(8)$$

Where 8 is the laser wavelength, P is the power at the exit pupil expressed in Watts, A is pupil area in square centimeters (cm^2), Σ is the solid angle subtended by the display to the eye and is defined as $2*(FOV_{Vertical})*sin(FOV_{Horizontal}/2)$., and K is the luminosity factor (598.67 for 532 nm).

Based on the assumed values, the predicted corneal power density was calculated to be 315 µW/cm^2. Microvision's calculation of maximum permissible exposure (MPE) based on above assumptions produced a value of ~585 µW/cm^2, a safety factor of 1.9 for normal operation. An MPE value of 585 µW/cm^2 correlates with a luminance level of approximately 2790 fL at the eye.

To date, Microvision has identified the two most relevant possible failure modes as 1) EPE failure and 2) scanner failure. In each case a higher energy density would be delivered to the eye. Microvision analysis suggests that for EPE failure alone, safe viewing would be limited to approximately 79 seconds (1.3 minutes); for simultaneous failure of both vertical and horizontal scanners, safe viewing would be limited to 32 seconds (0.5 minutes); for concurrent EPE and scanner failure, safe viewing without appropriate fail-safes would be reduced to an unacceptable 120 ms.

To address the possible failure modes, Microvision is designing fail-safe procedures that monitor excessive luminance (energy) at the EPE and the operation of both vertical and horizontal scanners. Additional maintenance safety measures already being incorporated include engineering controls such as appropriate warning labels and enclosure interlocks. Electronic fail-safe measures that produce system shutdown within a time period range of 5 ms to <50 µs are being explored.

In September 2001, Microvision submitted a laser product report to the CDRH, documenting a single unit prototype of the AIHS system as Class 1 system. Specifications cited in the report were as follows: wavelength (532 nm), maximum average radiant power (12.6 µW), field of view (0.367 sr), and beam diameter at exit pupil (15 mm). The Class 1 limit was evaluated under the 2001 revision to the IEC 60825-1 Safety of Laser Products – Part 1: Equipment classification, requirements and user's guide.

Proposed safety evaluation plan

    The U.S. Army Center for Health Promotion and Preventive Medicine (USACHPPM), Aberdeen Proving Ground, Maryland, is the Army's lead agency for laser hazard analysis. Its mission is to provide technical support for implementing preventive medicine, public health, and health promotion/wellness services throughout the Army. This mission encompasses non-ionizing radiation sources such as lasers.

    The U.S. Army Aeromedical Research Laboratory (USAARL), Fort Rucker, Alabama, serves as a technical consultant and independent test and evaluation facility for numerous Army HMD programs. USAARL has performed image quality system performance evaluations on three concept and prototype versions of the Microvision AIHS system (Rash et al., 1999; Harding et al., 2001a,b). Due to USAARL's involvement in the Microvision AIHS program and experience in aviation HMD applications, USAARL has been tasked by PM-ACIS to coordinate and supervise of the AIHS laser safety assessment.

    USAARL's role is to coordinate the various elements necessary for certifying the safe operation of the AIHS with USACHPPM and other necessary Army agencies. As a first step in fulfilling this role, a proposed approach to addressing AIHS laser safety has been developed. The approach consists of a series of tasks which USAARL feels will address regulatory requirements and health hazard assessment issues, as well as provide the extra measure of safety evaluation needed to overcome current aviation concerns regarding a laser-based HMD design.

    It is hopeful that this outlined approach to the laser safety program will be useful in the development of a documentation package that verifies the aviation eye-safe use of the Microvision AIHS scanning laser HMD during both normal operation and in the event of a system failure. It is anticipated that the proposed approach would be equally applicable to other laser-based HMD systems developed by the U.S. Army.

    The goal of this enhanced approach is the preparation of a documentation package that verifies the aviation eye-safe use of the Microvision Scanning Laser Helmet-Mounted Display (HMD) or other immersion display systems which utilize laser(s) as an "into the eye" imaging display.

    The anticipated elements of the proposed approach should include, but are not limited to, the following:

- A theoretical calculation of irradiation levels to the eye under normal operating conditions and available range of laser(s) intensity with comparison to maximum permissible exposures (MPEs). MPEs should be based on the most currently accepted standard.

  Microvision application: Calculations should be based on a 7-mm circular exit pupil, maximum achievable luminance (>1400 fL), 532 nm wavelength, and treatment of system as an extended source. Currently, the accepted standards for MPEs are the ANSI Z136.1 (2000) and IEC 60825-1 (2001 Revision).

- Verification of above theoretical irradiation levels by direct power measurements at the eye.

    Microvision application: Measurements should be taken using current AIHS configuration operating in a normal mode. Operational conditions should include a 7-mm circular exit pupil and minimum luminance of >1400 fL.

- Identification and implementation of all required external warnings on system, as required by the most currently accepted standard.

    Microvision application: Because current development phase is that of prototype, a full implementation of posted warnings may not be warranted. However, full identification of required labeling is recommended, and a minimum warning label configuration should be adopted to serve as reminder to engineering and maintenance personnel.

- The identification and implementation of all safety interlocks to effect complete laser shutdown when system enclosure(s) is opened. (Interlock defeat strategies allowing maintenance access are allowable, but must require positive effort to effect.)

    Microvision application: Although prototype phase will often require interlock defeat strategies, an identification, if not implementation, of full interlock requirements in accordance with ANSI and IEC requirements is recommended.

- Identification of major fault modes.

    Microvision application: A detailed fault analysis could be conducted to identify most probable major failure modes. Possible fault modes include loss of vertical deflection, loss of horizontal deflection, and reaction to power surges.

- Identification of all possible contributing failure mechanisms that could lead to the major fault modes.

    Microvision application: Catastrophic failures can result from cascading failure sequences. Reverse fault analysis should be performed in order to identify such potential sequences.

- Functional and engineering descriptions of failure mode interlocks and failsafe circuitry incorporated to implement solutions to major fault modes.

    Microvision application: In particular, designs for failsafe circuits to handle failures of scanning deflection circuits could be developed and documented.

- A detailed test plan for validation of incorporated interlocks, failsafe circuitry, and safety features. Measurements should include, but are not limited to, irradiation levels at the eye prior to, during, and after fault inject and system shutdown response.

  Microvision application: A detailed test plan should be developed to validate all incorporated interlocks, failsafe circuitry, and safety features. Fault injection techniques should be used to validate operation of safety features based on measured energy levels present at the design eye position for operating conditions listed above

- Government witnessed testing of fault injection and system response, verifying a full implementation of a fault detection and system shutdown capability.

  Microvision application: A demonstration of fault injection testing should be witnessed by USAARL.

The documentation package should contain data to verify all above elements. Suggested sources for methodology and proper reporting procedures include the following:

- DI-SAFT-80101B, System Safety Hazard Analysis Report, 31 July 1995 to identify and evaluate the system's hazards. It describes in detail tasks and activities of system safety engineering required to identify, evaluate, and eliminate/control hazards, or reduce the associated risk.

- DI-SAFT-80102B, Safety Assessment Report (SAR), 31 July 1995, a comprehensive evaluation of the safety risks being assumed prior to test or operation of the system or at contract completion. It identifies all safety features of the system, design, and procedural hazards that may be present in the system being acquired, and specific procedural controls and precautions that should be followed

<u>Summary</u>

A novel HMD design is under development for use in Army aviation. Referred to as the Microvision AIHS Scanning Laser HMD, it incorporates two laser sources that are used to form imagery viewed by pilots during flight. This system represents the first time that laser energy is purposely directed into the pilot's eyes as part of normal operation. Although this system is currently only in prototype phase, it has the potential of becoming a fielded system. In addition to ensuring that the system meets all standard laser related hazard and safety requirements, there is a need to provide expanded information regarding safety to the aviation community in order to overcome ingrained perceptions associated with viewing laser energy. The evaluation plan proposed herein consists of a series of tasks that, if performed and properly documented, is believed to address all of these concerns.

Recommendations

The next step in the laser safety evaluation of the Microvision AIHS scanning laser system is to implement the agreed upon elements of the evaluation plan proposed herein. Paramount to this evaluation is the actual measurement of power levels present at the exit pupil of the system. The confirmation of actual power levels and the comparison against predicted (theoretical) power levels would go a long way towards demonstrating an understanding of any potential hazards associated with the use of laser-based HMDs.

Disclaimer

The proposed laser safety evaluation plan presented herein is intended as a guide only and shall not be construed as the sole methodology for determination of the level of laser hazard. Such a determination is the responsibility of USACHPPM. Other tests, procedures, and documentation may be required.

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